

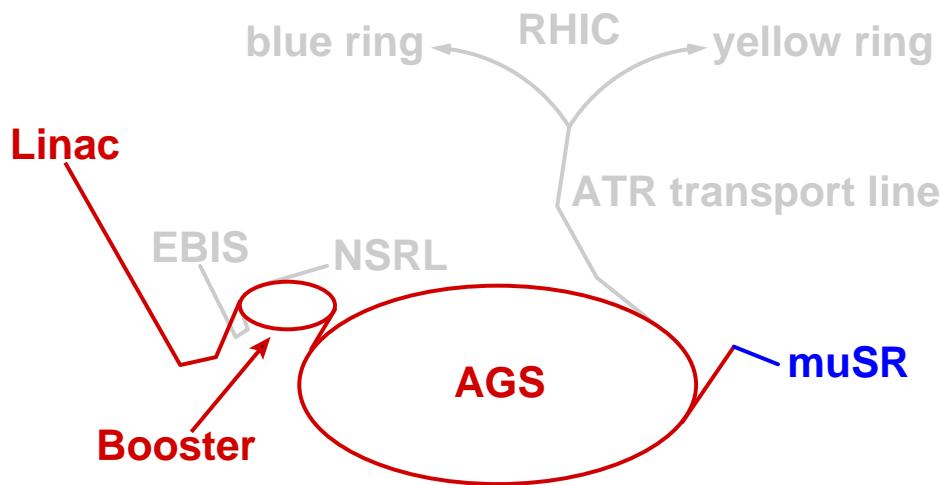
Muon Beamline Design at BNL

Waldo MacKay

with useful comments and ideas from:

Mike Blaskiewicz, Kevin Brown, Wolfram Fischer, and Phil Pile

Proton beam for surface muon beam



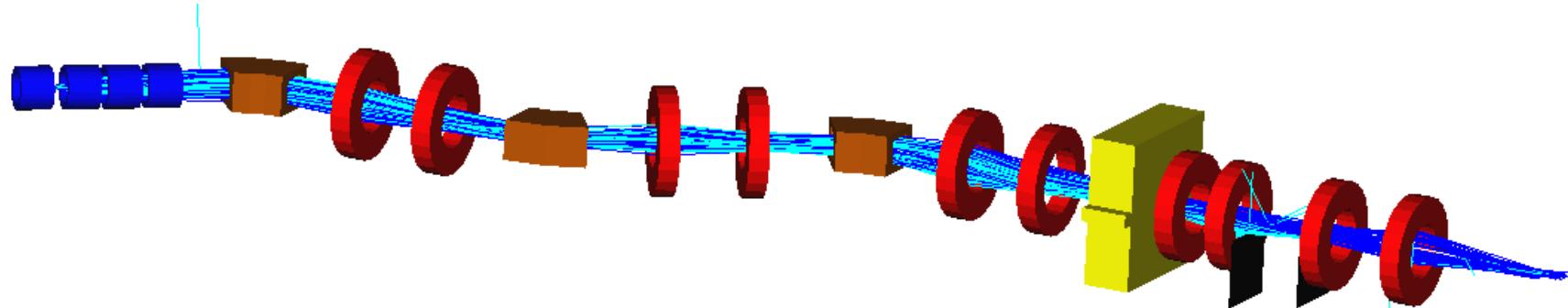
- Could use AGS ring as:
 - a simple transport line for pulsed operation, or
 - a stretcher ring for a DC beam.

- proton K.E.: 1.5 GeV at AGS extraction
- emittance: $\pi\epsilon_{95\%}^N = 50\pi \mu\text{m}$
- Booster repetition rate: 6.67 Hz
 - 1.5×10^{13} protons per spill
- AGS: 10^{14} protons/s
DC or pulsed

Surface muon beamline concept

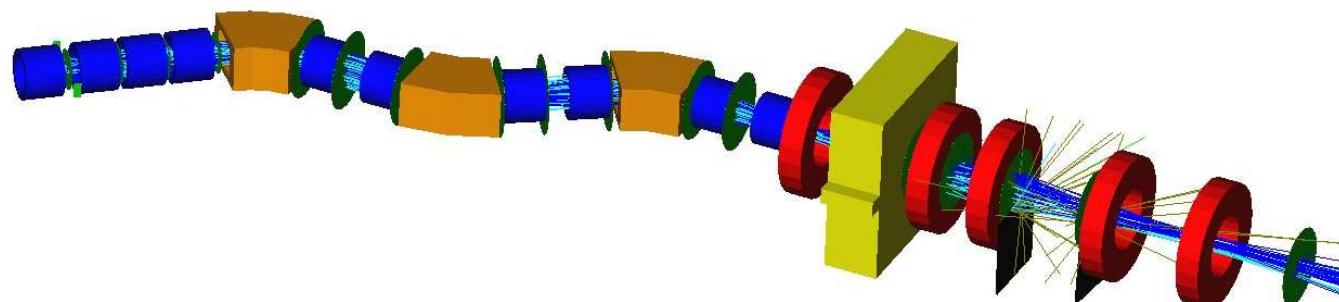
- Simulate with g4beamline (Vers 2.12) with QGSP_BERT.

Early version: like PSI μ E4 beamline with quad doublets ($L = 21$ m)



(IPAC13 THPWA052, M. Blaskiewicz et al.)

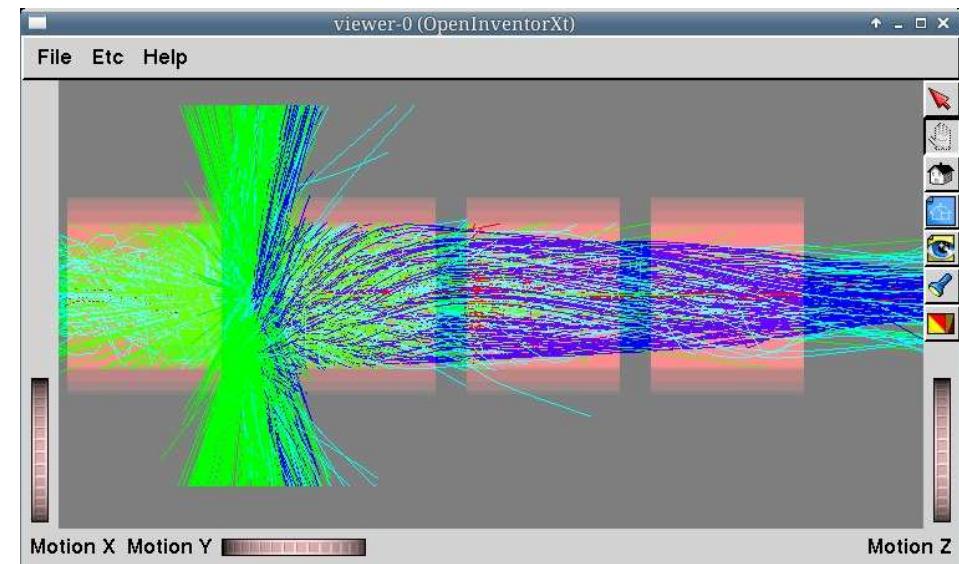
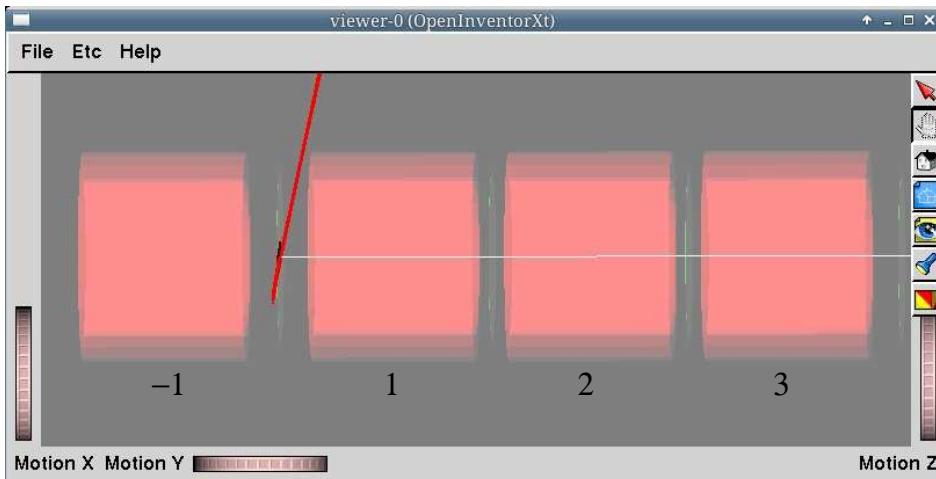
Latest version: replaced first three quad doublets with solenoid pairs ($L = 15$ m)



(C-A/AP/501, W. MacKay et al., “MuSR Beam Line Design Studies”, 2013)

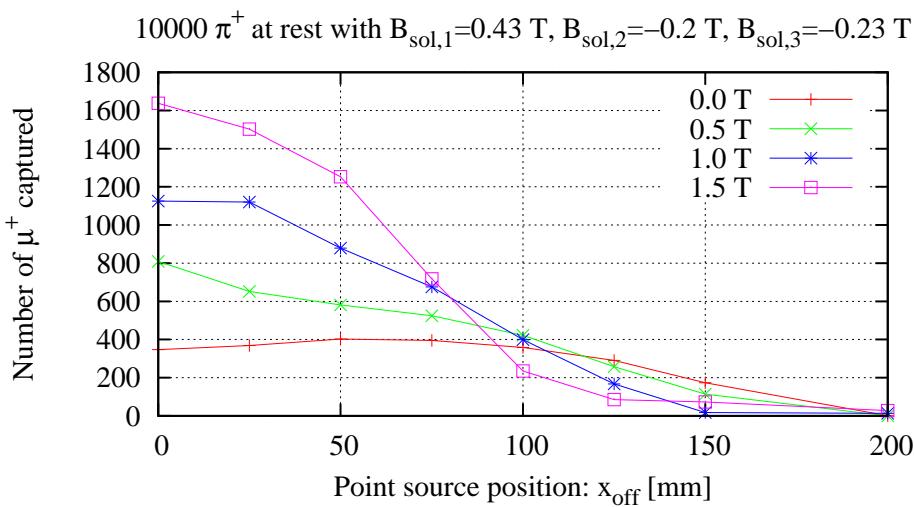
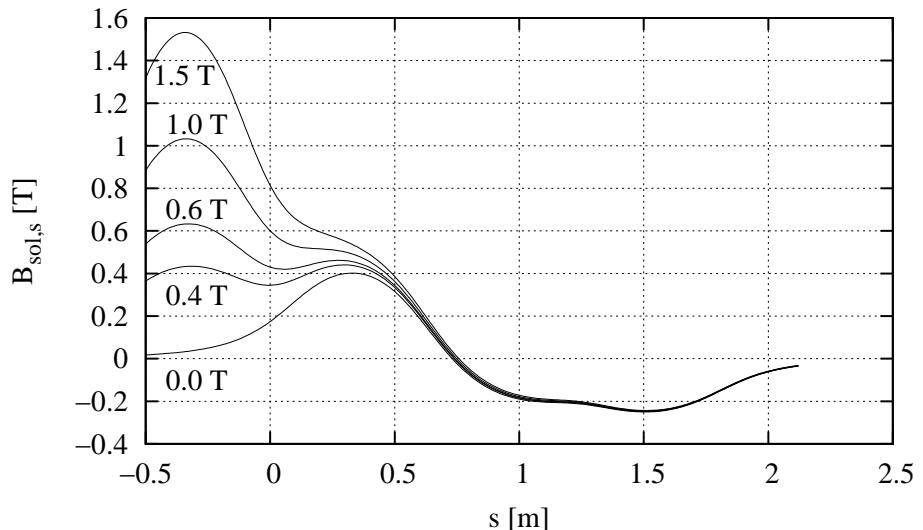
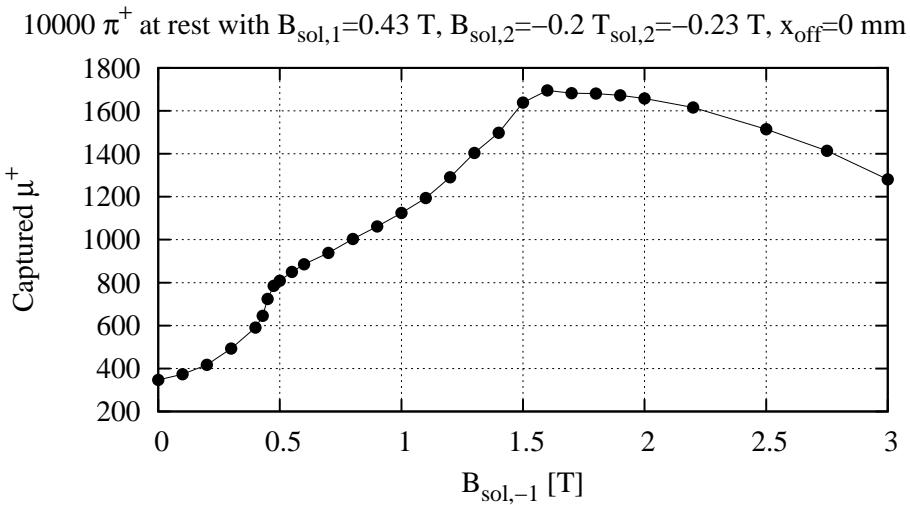
Capture solenoids

- solenoid length: 50 cm, inner radius: 24 cm.
- gap between -1 and 1 : 20 cm
- gaps between 1 and 2 , and 2 and 3 : 10 cm.



- Place 10,000 π^+ at rest on axis of solenoids at $z = 0$.
(i.e. midway between solenoids -1 and 1 .)
- Let them decay and look at μ^+ capture after last solenoid.

Scanning the upstream (-1) solenoid

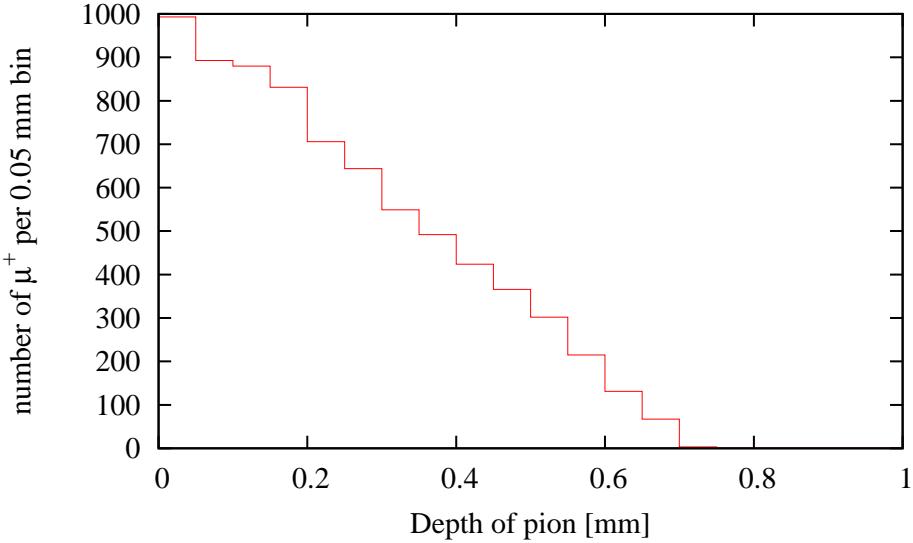


- $B_{\text{sol},-1} > 0$ captures more μ^+ .
- To decouple beam:

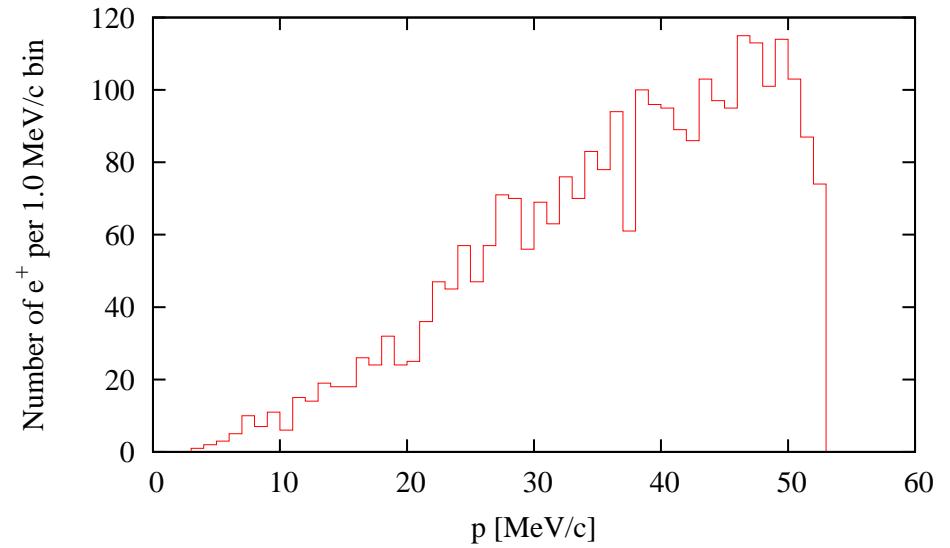
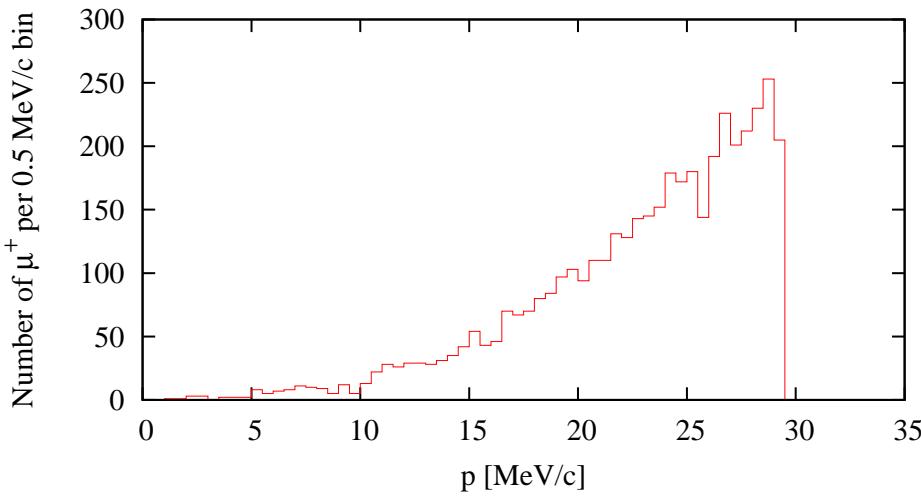
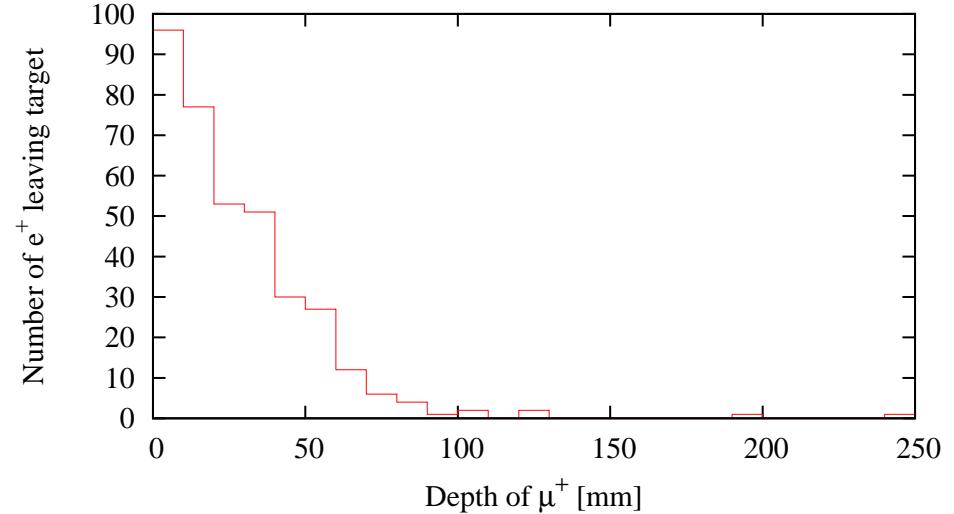
$$\int_0^{2.5\text{m}} B_z \, dz = 0 \quad \text{on axis.}$$

Decay of rest pions and muons in graphite

Rest $\pi^+ \rightarrow \mu^+ + \dots$

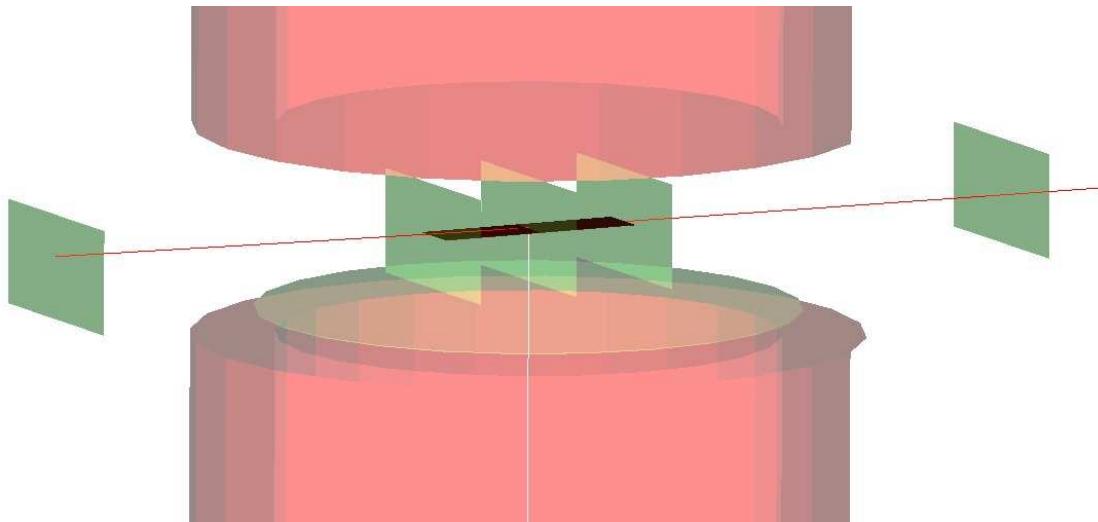


Rest $\mu^+ \rightarrow e^+ + \dots$



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Proton beam geometry with thin target

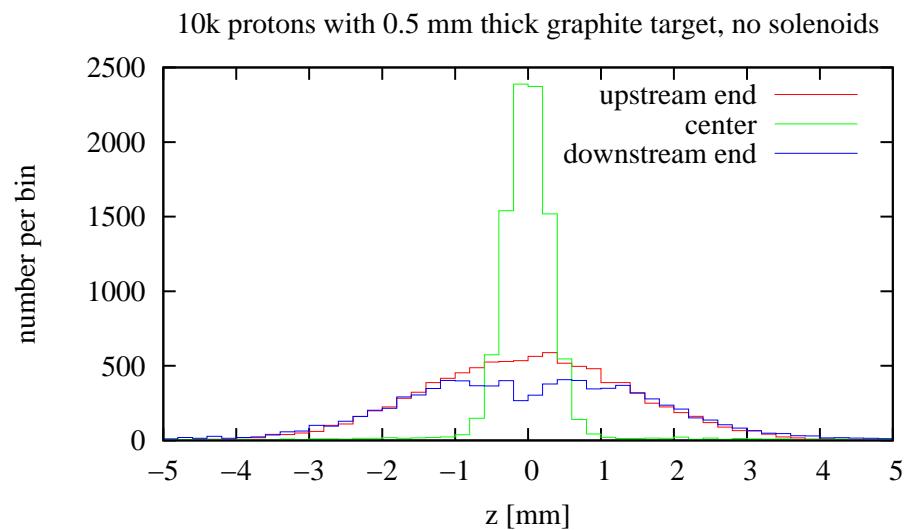
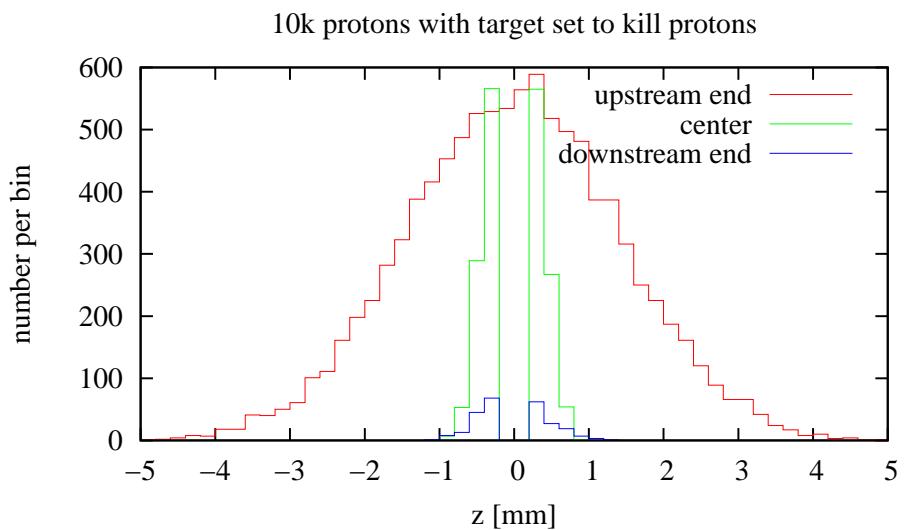
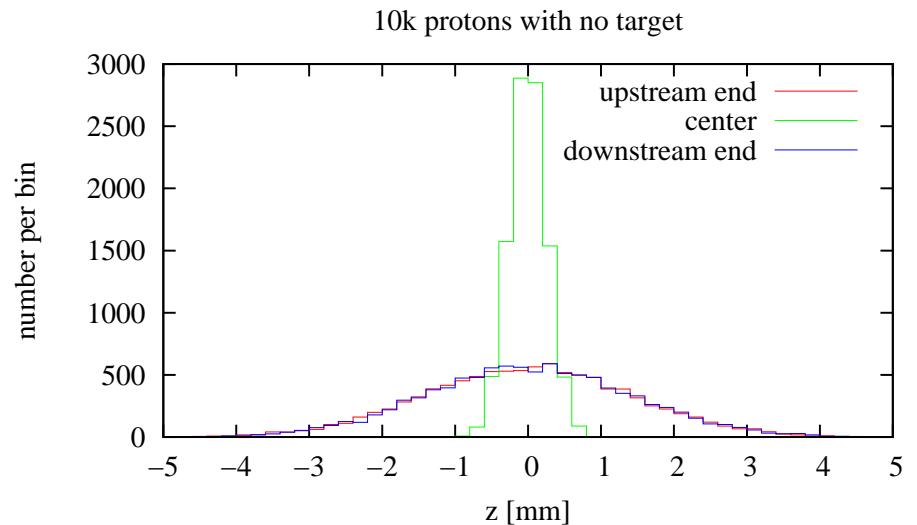
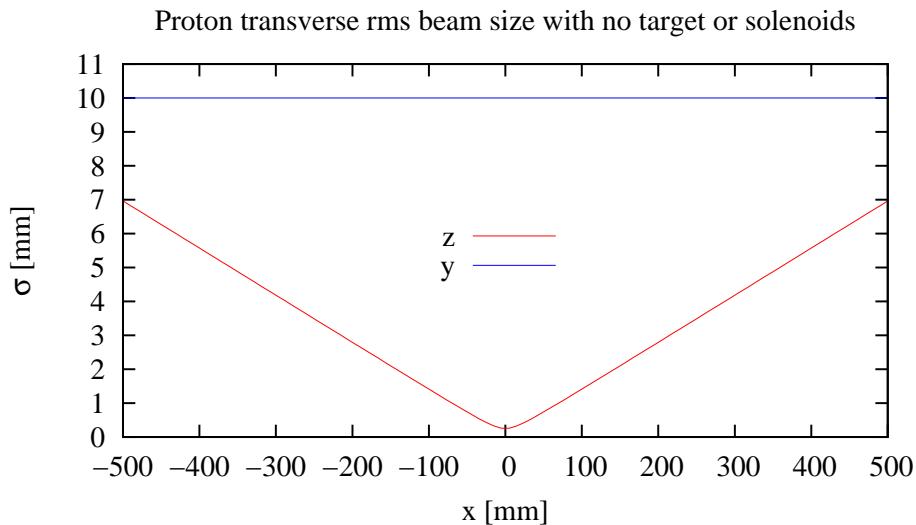


- Thin $200 \times 50 \times 0.5$ mm graphite target.
- Proton beam comes in from left along x -axis.
 - Emittance $\pi\epsilon_{95\%}^N = 50\pi \mu\text{m}$ in both planes.
 - $\sigma_z^* = 0.25 \text{ mm}$, $\sigma_y^* = 10 \text{ mm}$.
- 5 detectors along proton beam as shown:
 - placed at $x = -50, -10, 0, 10, 50 \text{ cm}$.
 - Solenoids off.

Overlap of protons passing through target

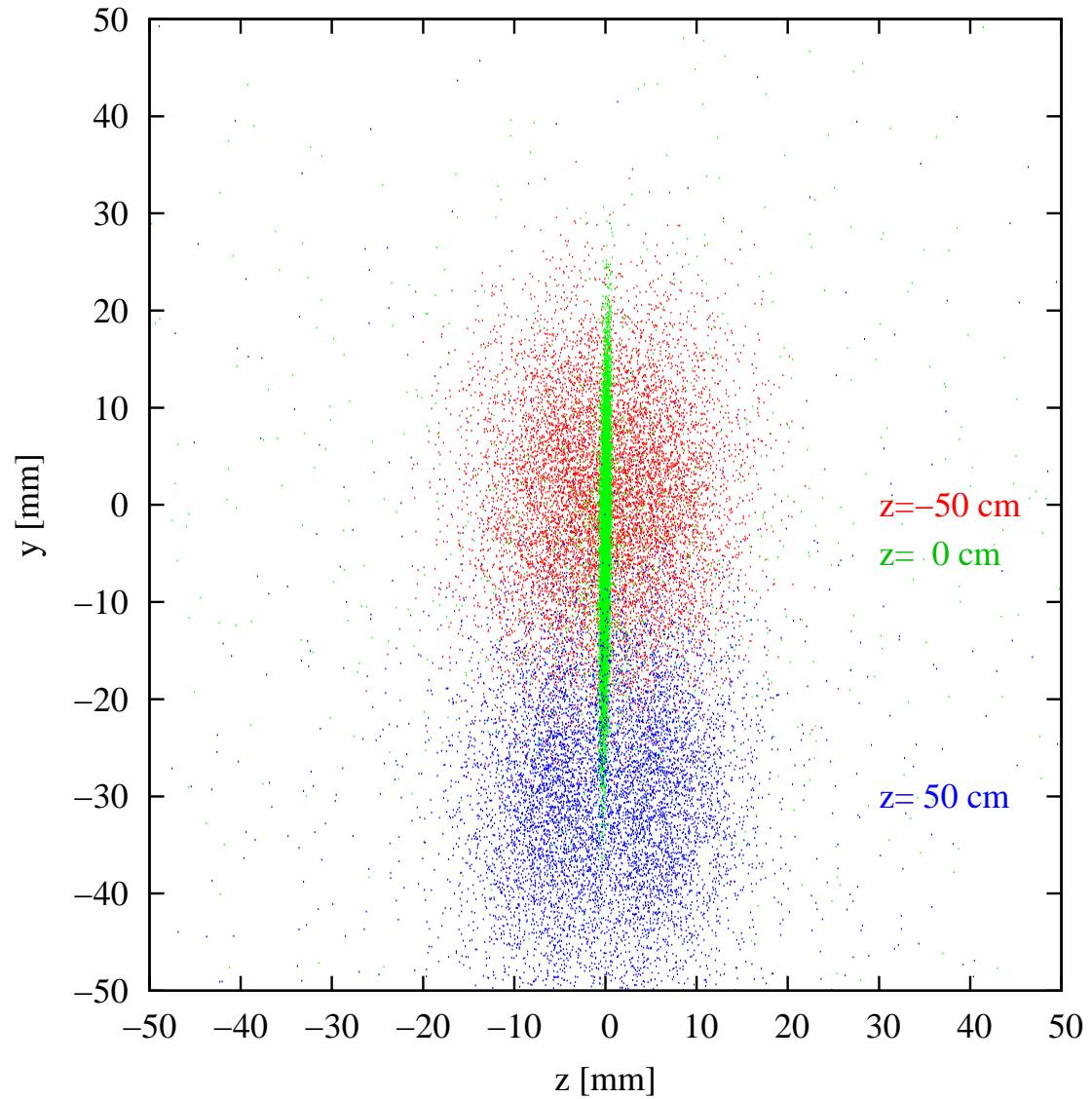


- Target (material = Vacuum, perfect absorber, and graphite).
 - 200×0.5 mm Segmented target (in black) with 2 cm segments.
(Segmentation used for energy deposition calculation. Actual target would be just a thin foil.)
- 200 protons (red) with kinetic energy 1.5 GeV.
 - $50\pi \mu\text{m}$, $\sigma_z^* = 0.25$ mm.



- Lower left: target kills beam (i.e. target = absorber)
- Lower right: target scatters beam
- Only showing protons.

- $B_{\text{sol},-1} = 1.5$ $B_{\text{sol},1} = 0.59$ $B_{\text{sol},2} = -0.4$ $B_{\text{sol},2} = -0.32$

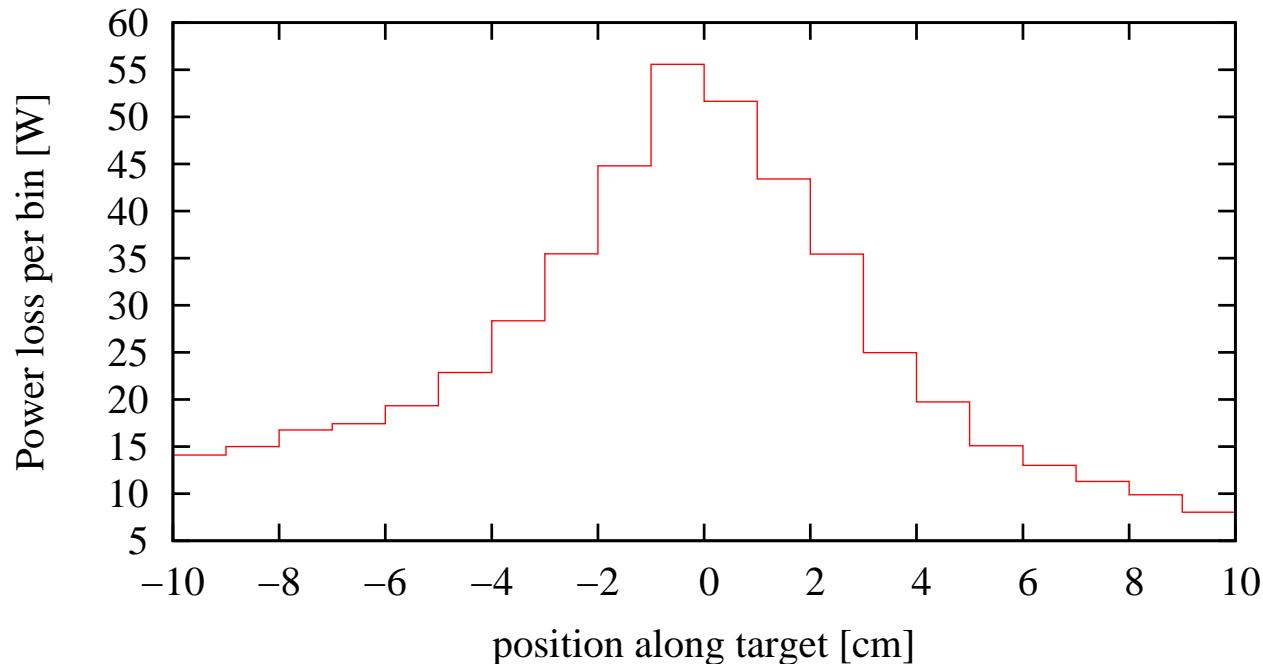


Power dissipation in target and solenoids

Element	Deposited Energy		Power (10^{14} p/s)
	Total [GeV]	per proton [MeV]	
target	320.6	32.06	513.0
sol-1	111.0	11.10	177.6
sol 1	113.2	11.32	181.1
sol 2	6.7	0.67	10.7
sol 3	0.6	0.06	0.95

- Simulated with K.E.=1.5 GeV beam of 10,000 protons.
 - Powers scaled up to 10^{14} protons/s.

Profile of power deposition along 200 x 50 x 0.5 mm graphite target



- Divide target into 20 segments with 0.1 mm gap between segments
(Gaps sum to 1% of normal target length.)
- Simulated with K.E.=1.5 GeV beam of 100,000 protons.
 - Powers scaled up to 10^{14} protons/s.
- No magnets, although I get a similar profile with solenoids.
- Total power on target summed to 498 W.

- Ignore heat conduction, and assume black-body radiation
 - Stefan-Boltzman law:

$$P = \epsilon \sigma A T^4$$

$$\sigma = 1.38 \times 10^{-23} \text{ J/K}$$

- Assume emissivity of $\epsilon = 0.98$ for graphite.

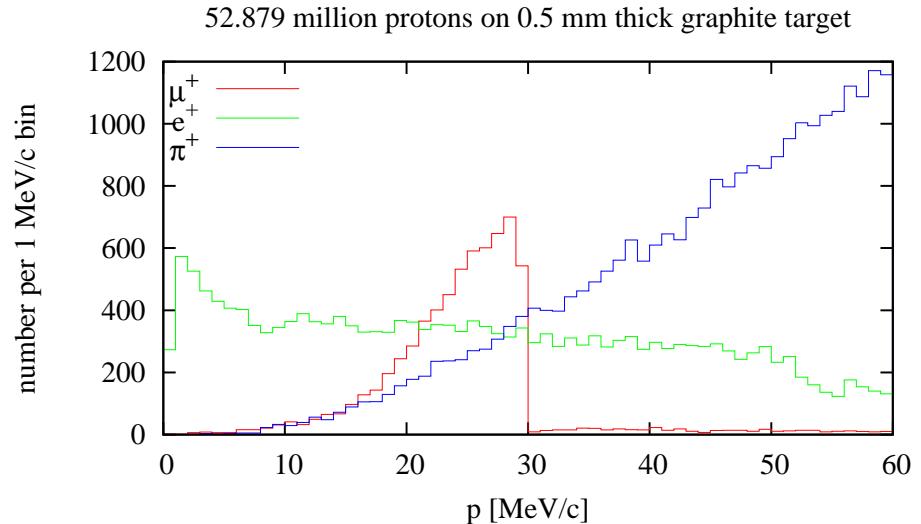
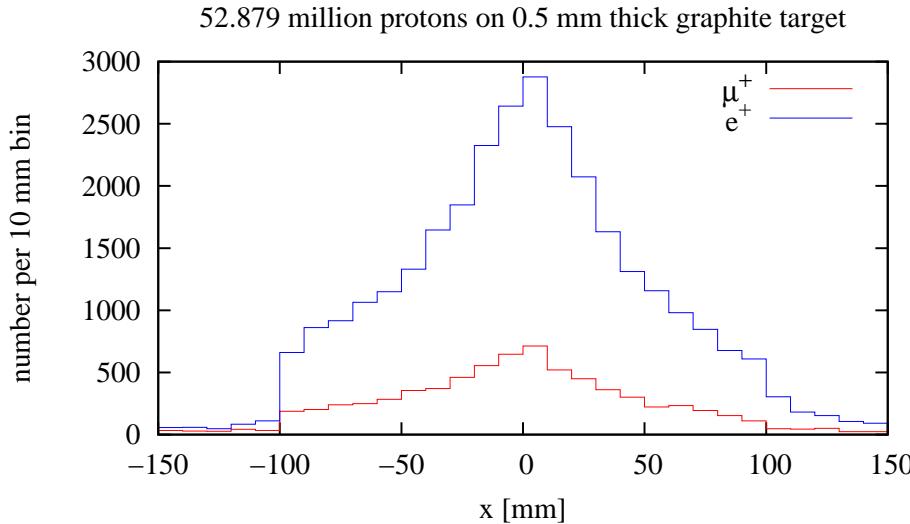
$$A = \frac{20 \text{ cm}}{20} \times 5 \text{ cm} \times 2 = 0.001 \text{ m}^{-2},$$

$$P = 55 \text{ W}$$

$$T = 960 \text{ K}$$

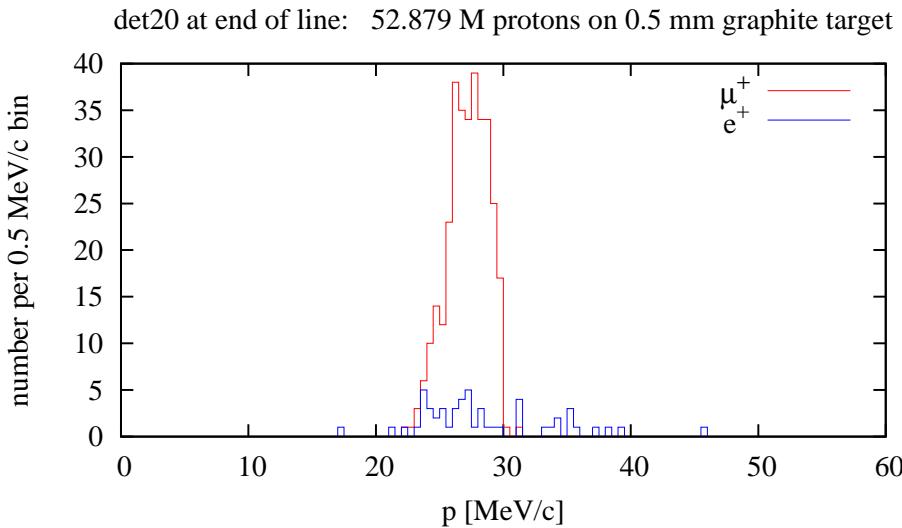
- For $\epsilon = 0.8$ [Haines and Tsai, ORNL/TM-2002/27]
this gives $T_{\max} = 1010 \text{ K}$.
- The 0.5 mm thick target should easily survive 10^{14} protons/s.
Graphite at $T = 1600 \text{ K}$ has a vapor pressure of 10^{-9} Torr .
[P. Thieberger, Tech. Rep. MUC-0186, BNL (2000)]

Muons and positrons just ds of target

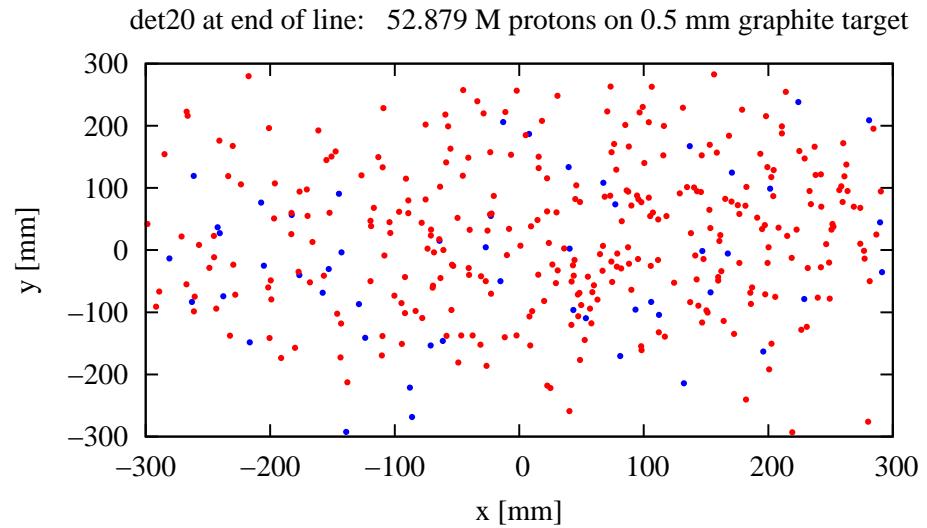


- 5.3×10^7 protons on target.
- secondaries detected 0.2 mm from surface of target.
- filter μ^+ , e^+ , and π^+ into separate files for reuse and tuning beamline, etc.

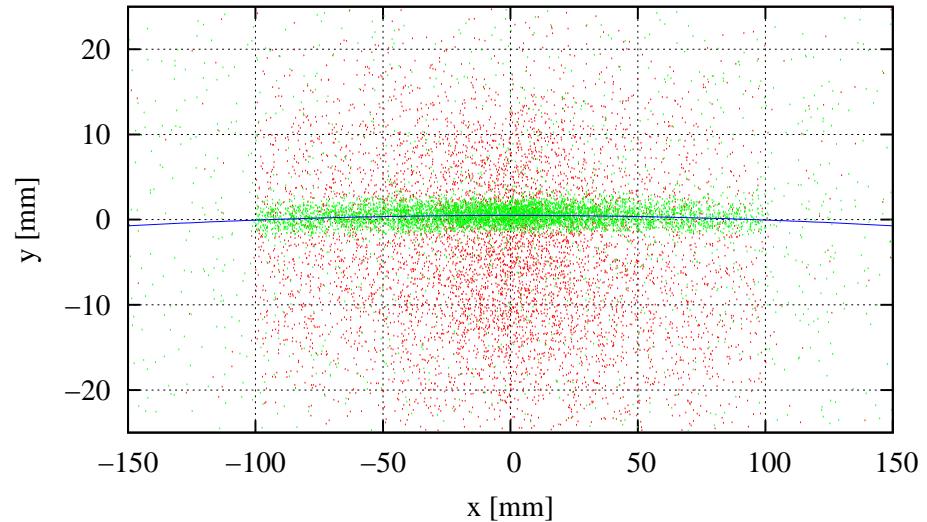
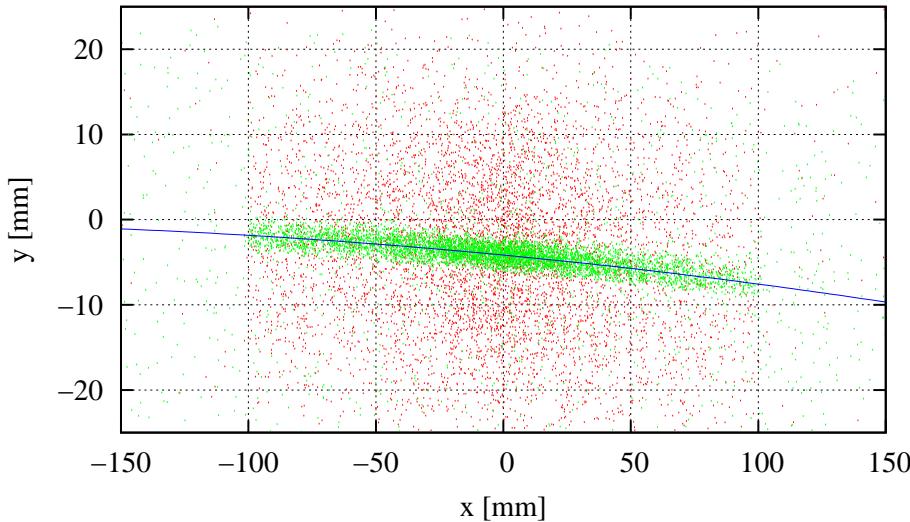
Muons and positrons at end of line



μ^+	e^+	Where
7512	32526	after target
2606	4542	after 3rd solenoid
1358	1338	after 1st bend
953	460	after 2nd bend
781	311	after 3rd bend
385	158	after separator
328	53	end of beamline



Reduce height of proton beam at target



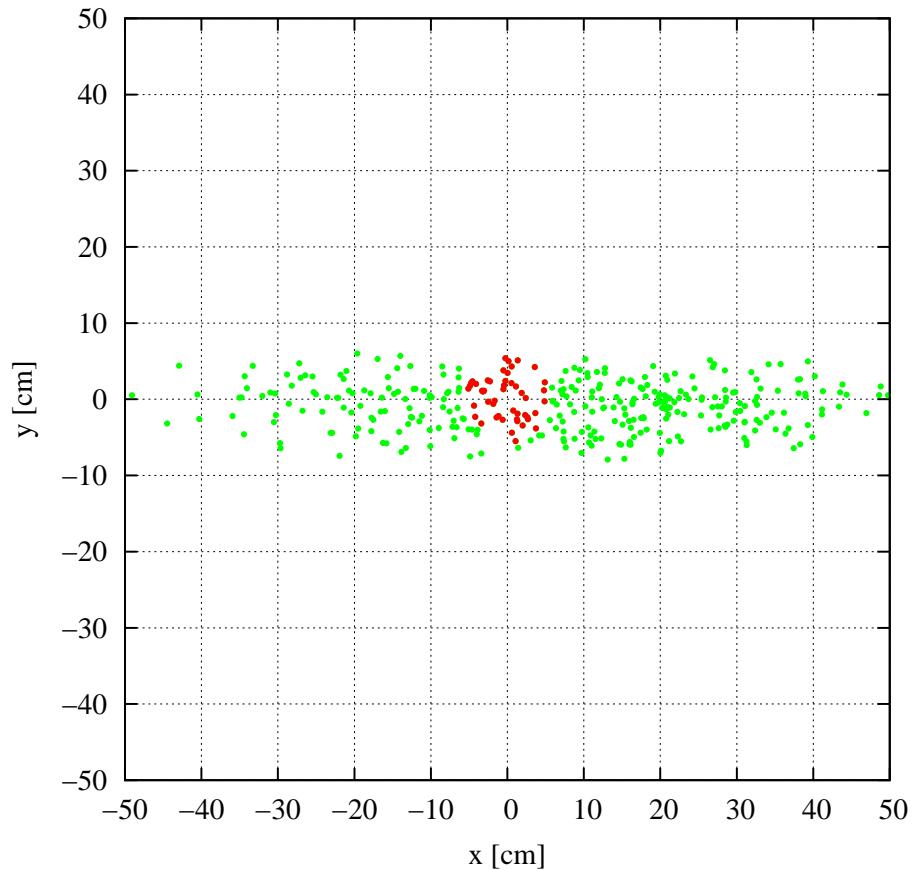
- μ^+ 0.2 mm ds of target
 - $\sigma_y^* = 10 \text{ mm}$ (red)
 - $\sigma_y^* = 1 \text{ mm}$ (green)

Transmission rates

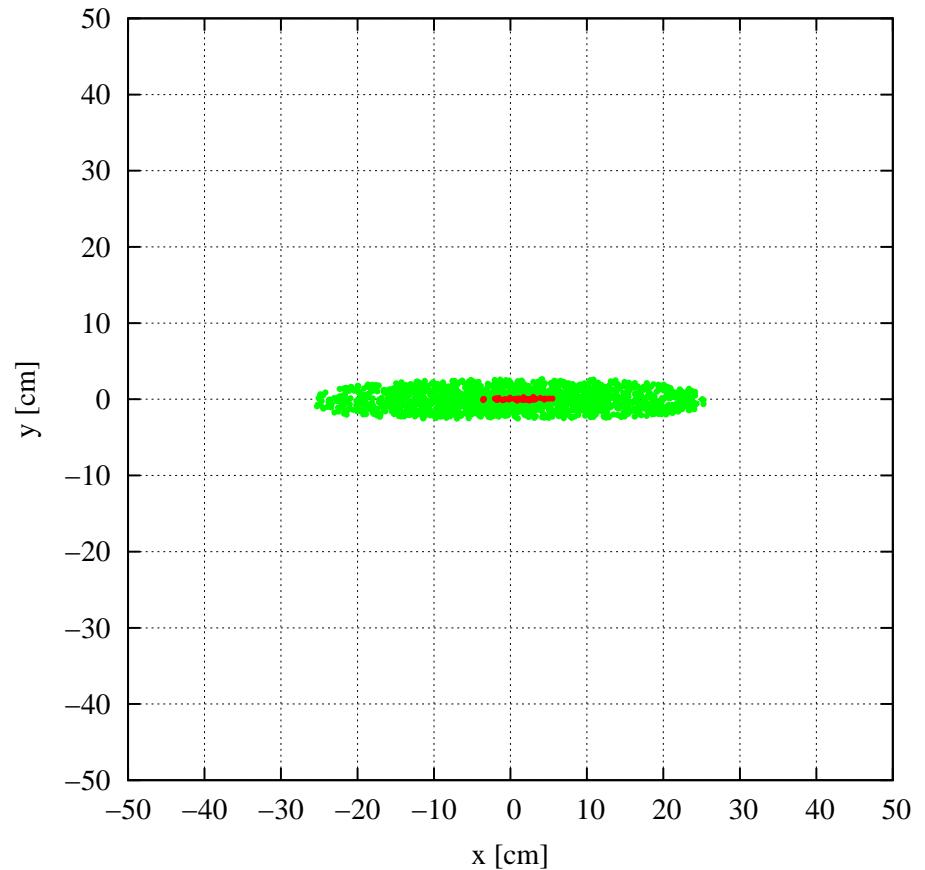
	det20 [MHz]	det21* [MHz/cm ²]
μ^+	660	0.91
e^+	91	0.13

* det21: 100 cm² ($r = 5.64 \text{ cm}$) detector at end of line.

Backtracking from det21 to det20



Backtracking from det21 to 0.2 mm ds of target



Conclusions

- 1.5 GeV proton beam ($\pi\epsilon_{95\%}^N = 50\pi \times 10^{-6}$ m) at 10^{14} protons/second
 - Either pulsed at 6.67 Hz or DC.
- Graphite target $200 \times 50 \times 0.5$ mm.
- Proton beam sent down length of target and focused to $\sigma_z^* = 0.25$ mm.
 - μ^+ only come from last 0.7 mm of graphite.
 - Thin target greatly reduces the background and overall heating.
 - No extra cooling required for the target.
 - Estimated peak temp with no conduction: $\lesssim 1010$ K.
- Rates at end of 15.2 m long beamline:
 - μ^+ : 660 MHz and e^+ : 91 MHz over large field
 - μ^+ : 0.91 MHz/cm^{-2} and e^+ : 0.13 MHz/cm^{-2} .
 - $8.7 \times 10^{-9} \mu^+ \text{ cm}^{-2} \text{s}^{-1}$ per proton.
- For comparison PSI μ E4 line [Prokscha et al., NIM A 595, 317 (2008)]
 - $22 \times 10^6 \mu^+ \text{ cm}^{-2} \text{s}^{-1}$ (averaged over 9 cm^2).
(1.7×10^{-9} per proton).

Comments

- Our beamline design needs more optimization:
 - separator and scrapers not in optimum positions for the newer version.
 - could decrease the aperture of magnets downstream capture solenoids
 - retune capture for smaller aperture beam
 - possibility of second beamline on opposite side of target.
- Need to design the proton transport from the AGS to the muon target.
- Deceleration is under study: [W. Fischer talk at muSR2014, June 2014]
 - using superconducting RF: (some μ^+ accel., some decel.)
 - using moderator (dE/dx).
- Need to recalculate with other geant4 models (earlier QGSP_BERT, etc.)
[Bungau et al., PRST-AB **17**, 034701 (2014)]
 - The production rates could be lower than what I calculated.
 - Old experimental data [Cochran et al., Phys. Rev. D **6**, 3085 (1972)] was measured for 730 MeV protons.
Does this change much for 1.5 GeV?



Photo courtesy of Blue Heron Whitewater

(Waldo getting a faceful of water.)

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Beamline elements of latest design

Element	s_{up} [m]	Length [m]	Aperture [m]	Strength
Solenoids				
S(-1)	-0.600	0.5	0.24	1.50
S1	0.100	0.5	0.24	0.59
S2	0.700	0.5	0.24	-0.40
S3	1.300	0.5	0.24	-0.32
SA1	3.100	0.5	0.24	0.25
SA2	3.899	0.5	0.24	-0.25
SB1	5.599	0.5	0.24	0.25
SB2	6.398	0.5	0.24	-0.25
SC1	8.098	0.5	0.24	0.25
SC2	8.897	0.5	0.24	-0.25
Sector bends				
B1 (-40°)	2.000	1.0	0.4×0.5	0.0693
B2 ($+34^\circ$)	4.499	1.0	0.4×0.5	-0.0590
B3 (-34°)	6.998	1.0	0.4×0.5	0.0590

Element	s_{up} [m]	Length [m]	Aperture [m]	Strength
Quads			(radius)	[T/m]
Q1	9.497	0.3	0.5	-0.15
Q2	11.217	0.3	0.4	0.40
Q3	12.027	0.3	0.4	-0.45
Q4	13.567	0.3	0.4	0.30
Q5	14.867	0.3	0.4	-0.20
Separator			$(h \times w)$	
V	10.307	0.7	0.2×0.6	360 kV
				$B_x = -0.0221 \text{ T}$
Scrapers			(plane)	(setting)
C1	12.347		vert.	$\leq -0.250 \text{ m}$
C2	13.427		vert.	$\leq -0.090 \text{ m}$

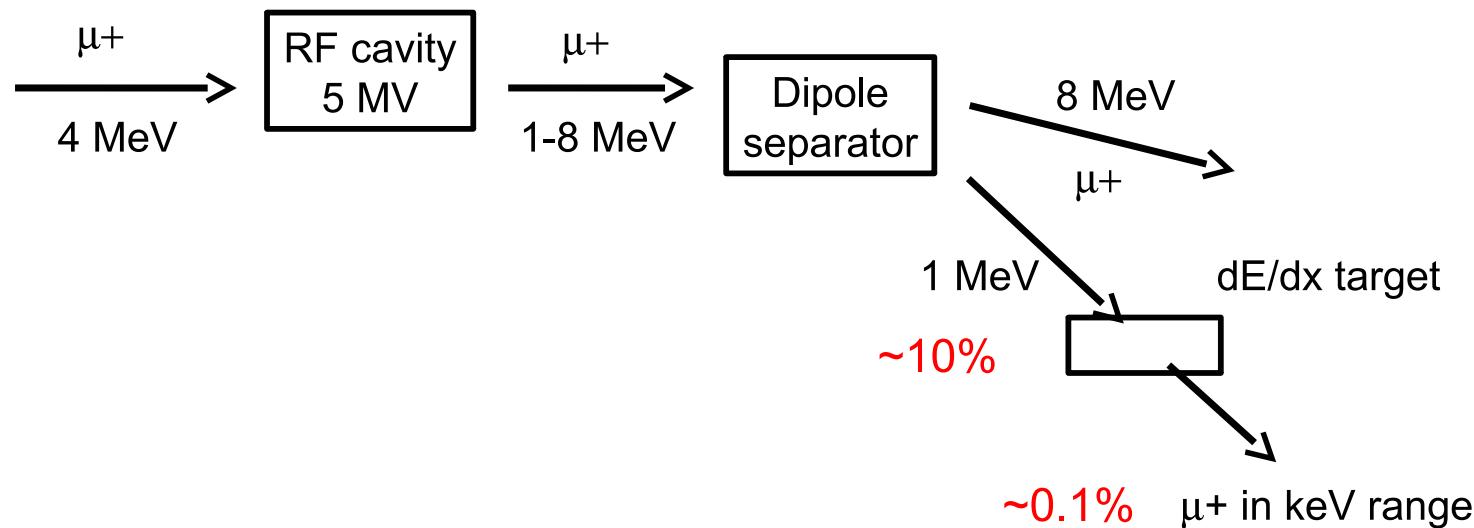
- Fields strengths set for 29.792 MeV/c muons.
 - optimum fields should be scaled down by 0.94 (28 MeV/c)

Muons at Brookhaven

Decelerating surface μ^+

Under study:

1. Decelerate (some) μ^+ with superconducting RF
(accelerates others)
2. Separate decelerated μ^+
3. Decelerate further through dE/dx target



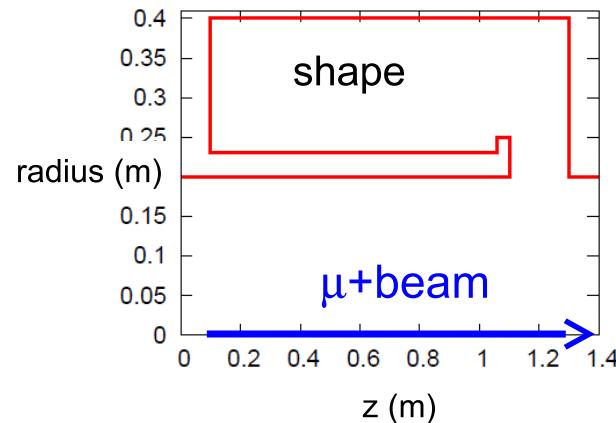
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(slide from W. Fischer's muSR2014 talk)

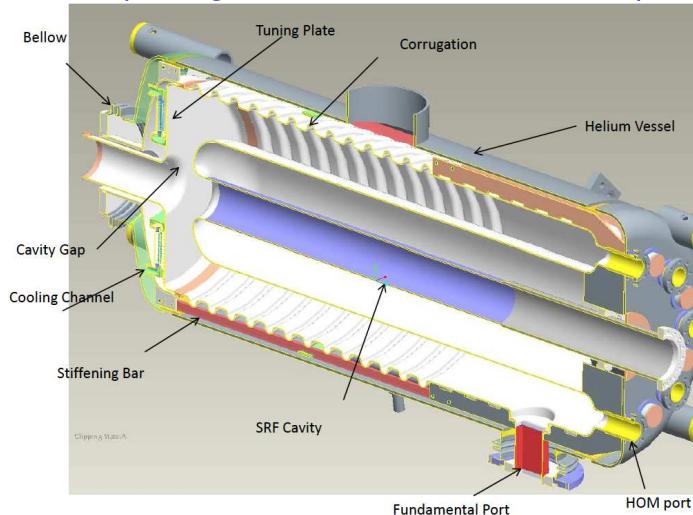
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Muons at Brookhaven

Basic cavity design: $V_{gap} = 5 \text{ MV}$, $f_0 = 64 \text{ MHz}$ and $3f_0$



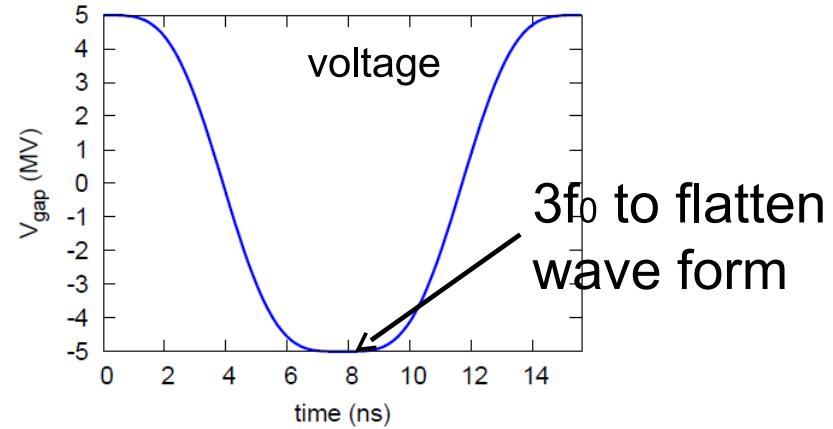
Existing RHIC SRF cavity: $V_{gap} = 2 \text{ MV}$, $f_0 = 56 \text{ MHz}$
(design values, beam driven)



Mike Blaskiewicz

(slide from W. Fischer's muSR2014 talk)

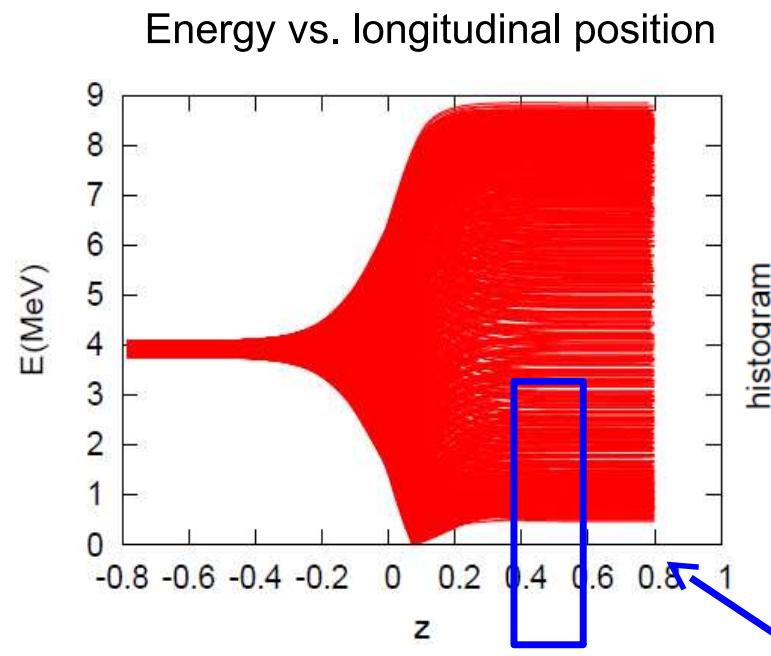
Decelerating surface μ+



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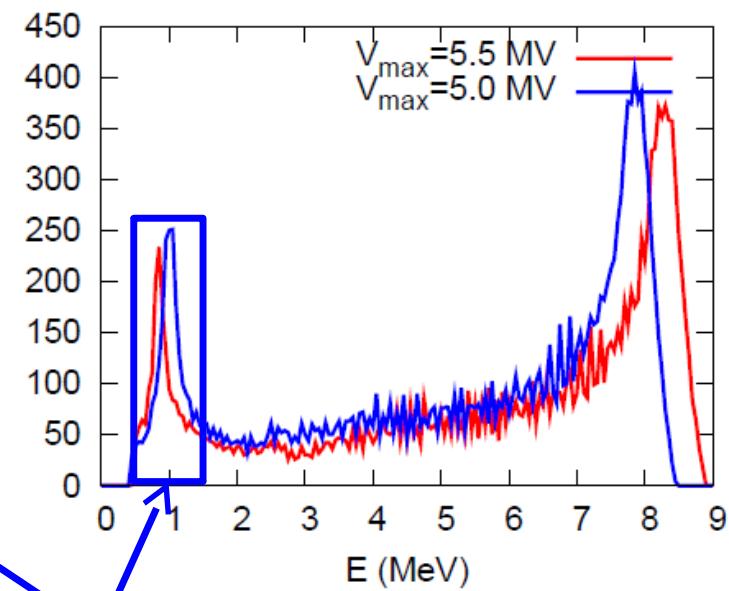
Muons at Brookhaven

Simulation of deceleration



Decelerating surface μ^+

Energy distribution after passage



(slide from W. Fischer's muSR2014 talk)



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Decoupling solenoids

Using canonical momenta, symplectic integration through capture solenoids gives the transport matrix on axis:

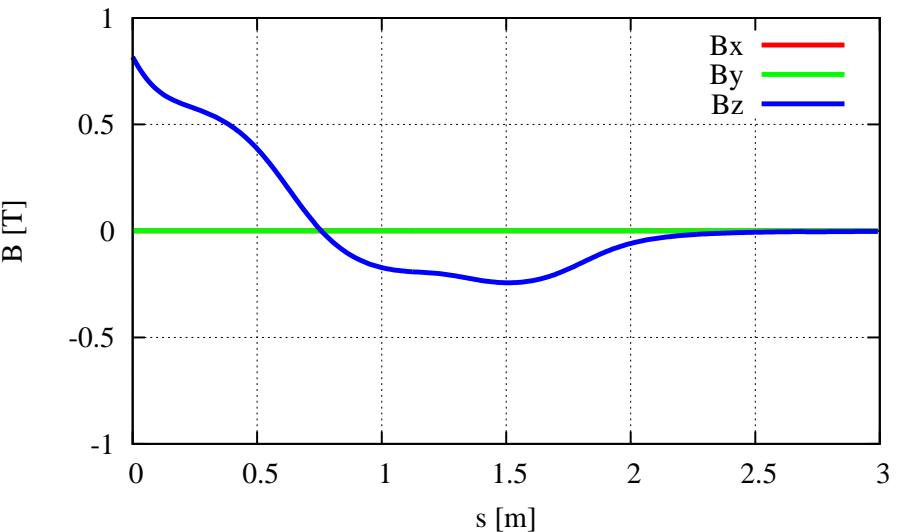
$$\begin{pmatrix} 2.007239 & -0.596408 & 0.000003 & -0.000001 \\ 3.003413 & -0.394202 & 0.000005 & -0.000001 \\ -0.000003 & 0.000001 & 2.007239 & -0.596408 \\ -0.000005 & 0.000001 & 3.003413 & -0.394202 \end{pmatrix}$$

$$\frac{p}{q}\Theta = \int_0^{3\text{ m}} B_s ds = 3 \times 10^{-4} \text{ Tm},$$

or $\Theta = 3.9 \text{ mr.}$

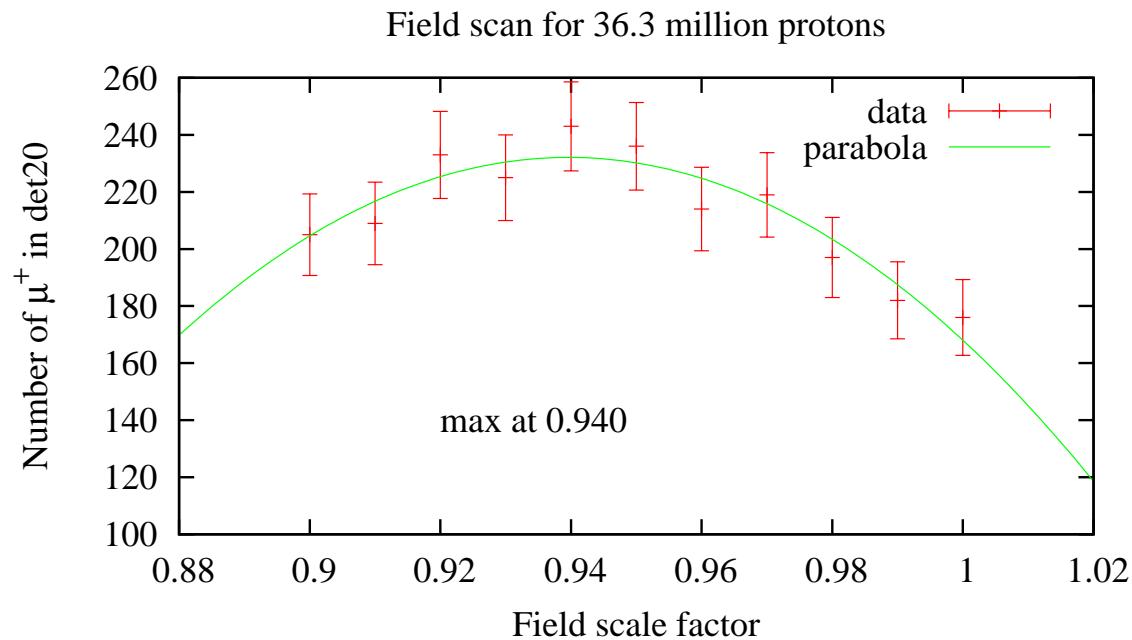
For Comparison:

$$\int_0^{3\text{ m}} |B_s| ds = 0.79 \text{ Tm.}$$



Momentum scan of beamline

- Initial design field settings were for 29.792 MeV/c μ^+ 's.
- Surface muons will be no higher in momentum, but can be lower.



- Field strengths should be lowered by 6% (28 MeV/c) for optimum transport.

Dispersion

